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FRP Strengthening of Web Panels of Steel Plate Girders against Shear Buckling under Static and Cyclic Loading

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ABSTRACT: The result of an experimental programme investigating a novel technique to strengthen web plates of steel plate girders against breathing fatigue is presented in this paper. The programme was divided into five phases, including: (1) the development of a novel preformed corrugated FRP panel for strengthening thin-walled steel plate girder webs against buckling, (2) selecting the appropriate adhesive and epoxy using double-lap shear and tension specimens, (3) producing the FRP panel, and (4, 5) testing its performance in two main experimental series. The initial series involved tests on 13 steel plates strengthened with the proposed preformed corrugated FRP panel and subjected to in-plane shear loading using a specially manufactured "picture frame" arrangement designed to induce the appropriate boundary conditions and stresses in the web plates of realistic plate girders; a description of this novel testing approach is included. This initial test series investigated the performance of different forms of strengthening under static load, in preparation for a subsequent series of cyclic tests to investigate their fatigue performance. The test variables included FRP type (CFRP or GFRP), form of FRP (closed or open section), number of FRP layers, and orientation of GFRP fibres used to build the FRP panel. This paper focuses on the second series, in which six specimens were manufactured to simulate the end panel of a 15m plate girder. These were strengthened with the optimized FRP panel from the first series and tested for shear buckling under repeated cyclic loading. Test results and non-linear finite element modelling showed the efficiency of the technique at reducing the critical stresses and increasing the fatigue life of the girders. Finally, the most appropriate strengthening method for fatigue performance is given on the basis of the work presented herein.

Keywords: Steel Bridges; Plate girders; Steel Plates; CFRP; GFRP; Fatigue; Buckling; Shear.

1. Introduction

Steel and composite steel-concrete bridges constitute a large number of the existing bridges worldwide. In 2008, it was reported that 72,520 bridges in the United States were structurally deficient (about 12% of the total), while the number of functionally obsolete bridges was more than 79,804 (about 13.3% of the total) (Bureau of Transportation Statistics, USA, 2008). Steel bridges comprise about 50% of the structurally deficient bridges and almost 40% of those that are functionally obsolete. The need for adopting durable materials and cost-effective strengthening techniques is therefore self-evident.

Different techniques exist for strengthening structures; all of which have drawbacks. For instance, conventional techniques for strengthening steel structures (such as welding additional transverse/longitudinal stiffeners) require heavy equipment during installation, their fatigue performance can be of concern, and may be a need for ongoing maintenance due to corrosion attack. Amongst the available strengthening techniques, the use of fibre reinforced polymers (FRPs) is appealing because of their resistance to corrosion, low weight, and high tensile strength.

The project presented in the current paper examines strengthening of the webs of steel plate girders against shear buckling using externally bonded FRPs. In-plane loading of thin web plates close to the shear buckling load results in out-of-plane displacements, which in turn induces secondary bending stresses at the welded web plate boundaries. Under repeated loading the combination of membrane stresses with these secondary bending (or "breathing") stresses may result in fatigue cracking and failure. In the current work, an FRP strengthening technique using bonded shapes is applied to reduce these out of plane deformations and hence the secondary bending stresses; see Fig. 1. This is in constrast to flexural strengthening, where the FRP provides additional direct tensile strength and stiffness.

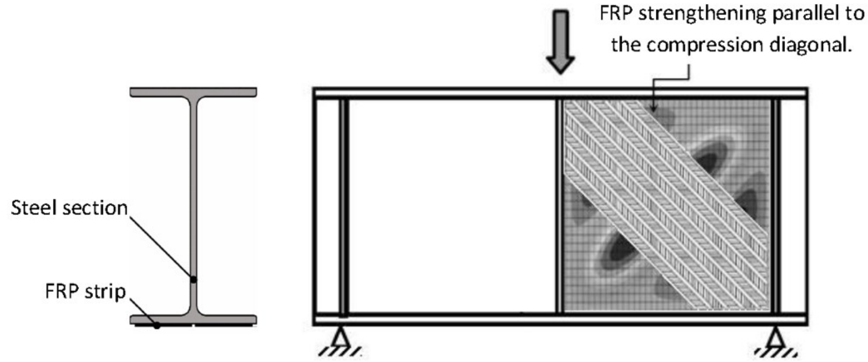


Fig. 1- Schematic showing the adopted shear buckling strengthening technique (b) compared to a typical flexural FRP strengthening (a).

2. Background

Roberts et al. (1995a) studied the rate of fatigue crack propagation and fatigue limit loads of slender web plates subjected to repeated shear loading. Their observations agreed with those of Yen and Mueller (1966), but they also presented a theoretical procedure for predicting the residual shear strength of fatigue-cracked web panels. They noticed that during fatigue tests the girders exhibited significant plate breathing, with pronounced shear buckles forming and reforming along the tension diagonals of the web panels. In general, fatigue cracks formed along the toe of the weld between the web and boundary members, in regions of relatively high secondary bending stresses, as indicated by the out-of-plane deformations. In addition, Roberts et al. (1995b) noted that stress ranges at potential fatigue crack locations can be predicted using nonlinear finite element plate analysis or approximate analytical solutions. They also indicated that the fatigue assessment procedures currently recommended in the Eurocodes, based on either principal stress ranges or normal and shear stress ranges, provide conservative estimates of the fatigue life of slender webs subjected to plate the breathing phenomena.

There have been some studies in which the webs of steel plate girders have been strengthened under short term shear loading, with a useful summary is included in Karbhari (2014). One example is presented by Okeil et al. (2009), who investigated the use of bonded GFRP pultruded sections for strengthening steel structures. In this work a GFRP section was bonded to thin-walled steel plates so as to contribute to its out-of-plane stiffness more than its in-plane strength, as is common practice in most FRP strengthening applications. Beam (shear) specimens were tested to explore the proposed out-of-plane strengthening technique, which succeeded in increasing the ultimate capacity of the strengthened specimens by 56%. The ductility of the strengthened specimens was, however, less than the unstrengthened ones. The authors are unaware of any literature addressing the fatigue problem of FRP shear strengthened steel plate girders, although there has been a variety of reserch examining the performance of FRP strengthening applied to steel in other fatigue configurations (Karbhari, 2014).

3. Experimental Programme

The objective of the experimental programme presented in this paper is to strengthen thin-walled steel girders against web shear buckling using a novel corrugated CFRP and GFRP panel. The effectiveness of the method in enhancing the buckling stiffness and ultimate shear capacity of thin steel plates has already been proven by the authors during the first experimental series and has been reported elsewhere (Al-Azzawi et al., 2015a and 2015b).

In summary, the previous experimental programme had four phases. Saturating resins for wet lay-up of dry fibre sheets and bonding epoxy were selected based on their performance in double lap shear (DLS) coupons tested in tension. This was used in a second phase to manufacture direct tensile specimens to determine the mechanical properties of the FRP composites. Table 1 gives the material mechanical properties of the FRPs used in producing the panels for the current work, where *FVF*, f_{tf}, and E_{tf}, represent the fibre volume fraction, the tensile strength, and the Young's modulus of the fibre composite. Different FRP sections comprising a wide range of variables were produced in the third phase. These FRP section were used in the last two phases to test their efficiency under static and cyclic loads, hereafter called the initial (static) and final (cyclic) series of tests. In the initial series of static tests (phase 4), 13 steel plates were strengthened by bonding the preformed corrugated FRP panels along their compression diagonals; these were then tested for shear buckling under pseudo-static loads. The in-plane loading was applied using a specially designed "picture frame" testing rig that is capable of holding the steel plate under realistic boundary conditions under in-plane shear loading, to simulate the case in a real steel plate girder.

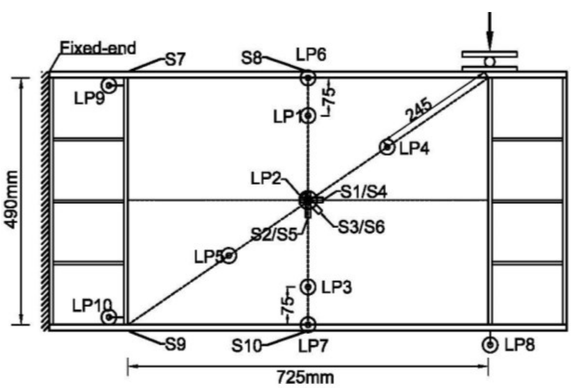
The work presented in this paper (phase 5) involves strengthening six plate girders using the optimized strengthening section from the initial series of tests and testing them under repeated cyclic loading to validate the efficiency of the strengthening technique and determine its fatigue enhancing properties.

Table 1- FRP Material properties

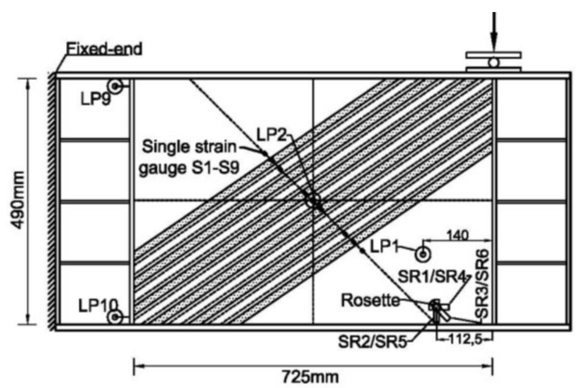
Specimen	*FVF*	f_{tf}, MPa	E_{tf}, GPa	Note
CFRP-450	0.59	704.2	48.1	3-Layers
GFRP-440-45°	0.48	61.6	18.0	3-Layers

3.1. Specimen Details and Test Instrumentation

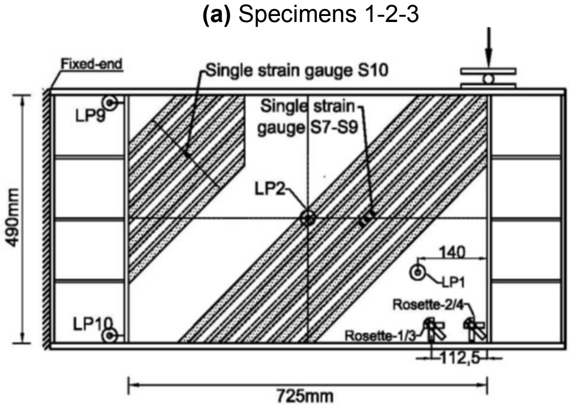
Fig. 2 illustrates the details of the test specimens used in this work. Only one panel of a steel plate girder was tested representing an end panel of longer plate girder where the high shear stresses can be expected.



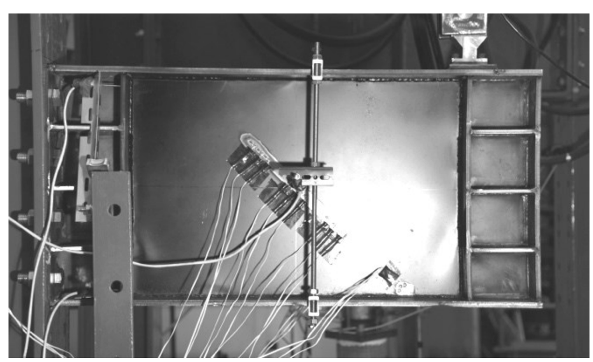
(a) Specimens 1-2-3



(b) Specimens 4-5



(c) Specimen 6



(d) Test setup

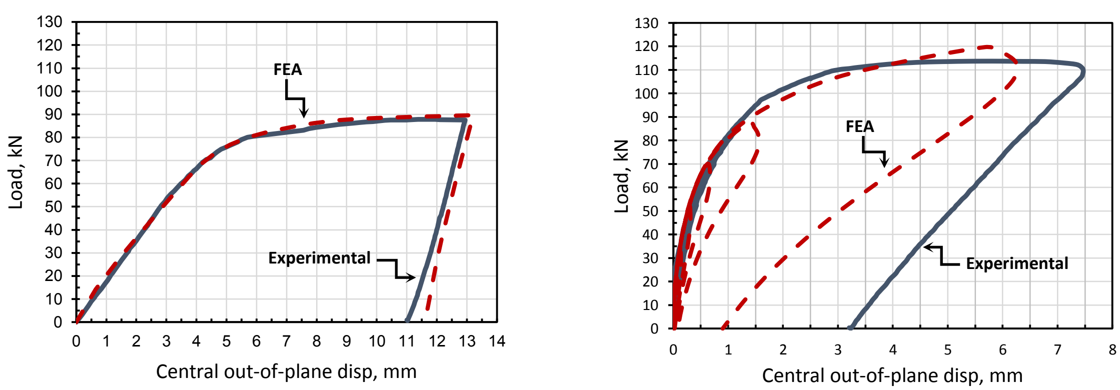
Fig. 2- Locations of strain gauges and LPs.

The cyclic test series tested 6 plate girders. The clear dimensions of the web panel was 725 × 490mm, giving an aspect ratio of 1.5. The web plate was made from an S275 steel plate with a thickness of 2mm. The slenderness ratio of the web (height divided by the thickness) is 245. This practically high slenderness ratio was chosen because it will help in showing the stiffening effect of the proposed FRP panel. The first 3 specimens were the control specimen, a GFRP strengthened specimen, and a CFRP strengthened specimen. These were tested for shear buckling under static load to serve as a precursor to the three subsequent cyclic tests. The static tests were performed using a 1000 kN Instron actuator at a displacement rate of 1.0 mm/minute. The strain gauge readings along with the displacement gauges (LPs) and the Instron actuator load were recorded using Vishay 7000 data acquisition system at a rate of 10.0 Hz. The remaining three specimens where subjected to 2 million cycles of loads with an amplitude of 80% of the experimentally measured ultimate shear capacity of each specimen at a loading frequency of 2.0 Hz prior to their final residual test. One exception to this was the GFRP strengthened specimen which was exposed to 1 million cycles of loads only, this is due to the fact that this specimen exhibited no significant breathing during testing due to its reversed initial imperfection shape. As shown in Fig. 2, specimens 4 and 5 are a GFRP and CFRP strengthened plate girders, respectively, while the sixth specimen was a CFRP strengthened one but with a 45° angle of inclination instead of the diagonal angle (34°) adopted in all previous specimens.

4. Finite Element Analysis to Examine Plate Buckling and Stresses

It is very difficult to directly measure the very localised secondary bending stresses that result in the breathing fatigue failure that is of interest, consequently a non-linear FEA model (using Abaqus 6.10) was used to model the experiments. The model was compared to the experimental results, and interrogated to determine the resulting stresses.

The model was built using S9R5 elements, requiring a Matlab code to be used to create the node geometry and element incidences from which an input file was created. The initial imperfection was found using elastic Eigen buckling modes, and the magnitude of initial imperfection measured in the test specimens was applied using Abaqus script commands in the input file. Elastic-perfectly-plastic stress-strain curve was adopted for the steel constitutive model with a modulus of elasticity of 200GPa and yield strength of 275MPa. The GFRP was modelled using engineering constants constitutive model (available in Abaqus) with a modulus of elasticity of 14.4GPa. Default cohesive zone surface interaction was used to model the bonding area. Fig. 3a and 3b show verification curves for the specimens against central out-of-plane displacement (in-plane deflection and central strain was also verified with the same accuracy). NB: this agreement was obtained without recourse to “adjusting” the finite element modelling to obtain a good match.



(a) Control specimen **(b)** GFRP strengthened specimen

Fig. 3- Finite element model.

5. Experimental Results and Analysis

Table 2 shows the Experimental test results for the first three static specimens. As well as the ultimate load (P_u), the table illustrates the central maximum surface principal stress (σ_P), the maximum normal secondary bending stress (σ_n), the maximum principal surface shear stress (τ_P), the central out-of-plane displacement (δ), and the in-plane deflection (*Δ*); all at a load equal to the failure load of the control specimen for the sake of comparison. For specimens SP-2 and SP3, the maximum surface principal stress was reduced by 81% and 51% respectively, and the maximum surface principal shear stress was reduced by 89% and 77%. It is worth mentioning that the stresses in Table 2 were calculated mainly from the experimental strain except the cases where the data was not recorded properly due to a malfunction in the strain gauges during the test; such as S3 for SP-2 and S2 for SP-3, refer to Fig. (2.a) for their locations. These missing data were determined from the finite element model which was already verified. A considerable increase in the stiffness of the strengthened specimens is evident in the observed reductions of the maximum out-of-plane displacement, which was reduced by approximately 90% for both GFRP and CFRP strengthened specimens. Fig. 4 shows the buckling curves for these three specimens along with the hypothetical control specimens having the same initial imperfection predicted using finite element modeling.

Fig. 5 shows the residual buckling curves for the cyclic specimens (SP-4,-5,-6) and Fig. 6 shows the accumulated in-plane and out-of-plane displacements with the number of loading cycles. The strengthening scheme adopted in specimen 6 (45° angle of inclination, Fig. 2.c) performed better than the diagonal strengthening scheme both in stiffness and ultimate capacity as can be seen from Fig. 5, however, they both had the same ductile failure. From the figures it can be seen that the breathing phenomena represented by the out-of plane displacement is significantly reduced, consequently the secondary bending stresses are reduced. This in turn will increase the fatigue life estimation (using standard Euro code or ASTM S-N curves) of the strengthened specimens by a factor of 10 to 1 (shown in more detail in Al-Azzawi et al., 2015a). The proposed strengthening technique did not exhibit debonding even at ultimate load, which makes it ideal for strengthening structural members where ductility is crucial.

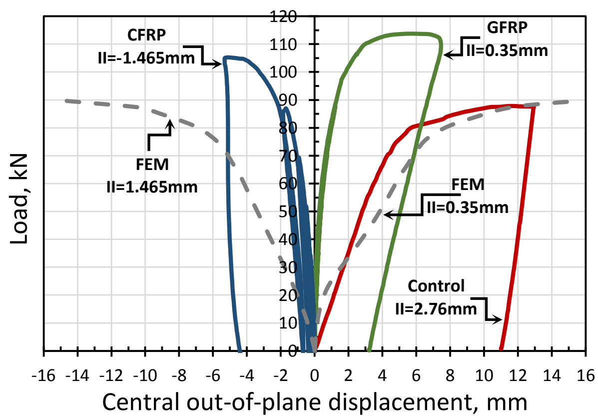


Fig. 4- Buckling curves of static tests

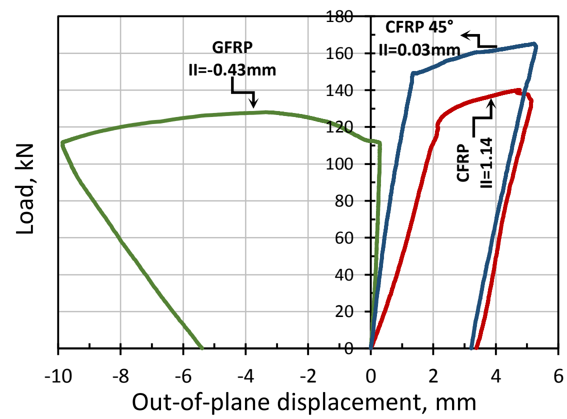
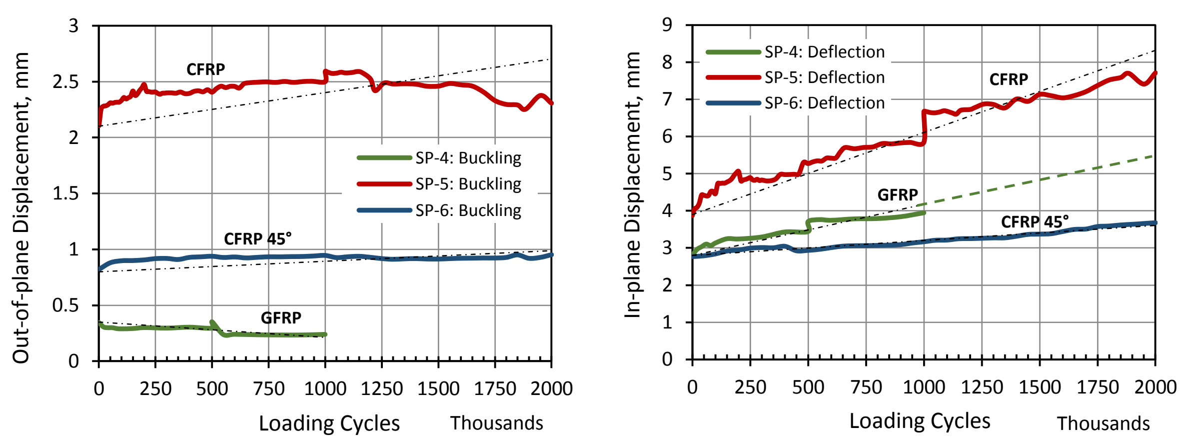


Fig. 5- Residual buckling curves of cyclic tests



(a) Maximum out-of-plane displacement **(b)** Maximum in-plane displacement

Fig. 6- Accumulated displacements under cyclic loading.

Table 2 - Experimental results of the static test specimens 1, 2, and 3

Specimen	Designation	P_u, kN	σ_P, MPa	τ_P, MPa	σ_n, MPa	δ, mm	Δ, mm	$P_u / P_{Control}$
SP-1	Control	87.87	+/-275.00	158.77	227.62	11.55	5.87	1.00
SP-2	GFRP	113.71	-52.6	16.99	-	1.23	2.76	1.29
SP-3	CFRP	105.24	133.65	36.36	-	1.25	2.42	1.20

6. Conclusions

A novel preformed corrugated FRP panel has been introduced in this study as a strengthening technique for slender steel plates (such as the webs of a plate girder) against breathing of plates, aiming at reducing fatigue failures. The section of the panel was optimized using finite element modelling that took into account minimizing the cost of the FRP material, the quantity of adhesive being used, workmanship, and the complexity of the multi-axial stress state in the web steel plate.

Two major series of experimental studies were performed. The initial series demonstrated the effectiveness of the proposed strengthening technique. The final series that is the focus of this paper tested the effectiveness of the optimized corrugated section under cyclic loading. Six specimens were fabricated to model the end panel of a typical plate girder; three of which were tested under static loading to serve as a precursor for the other three specimens that are tested for cyclic loading.

Fatigue analyses indicated that the proposed strengthening technique should be able to considerably reduce the secondary bending stresses at the web plate welded boundaries, and therefore elongate the life expectancy of some plate girders by a factor of 10. In addition, the proposed strengthening technique did not show any debonding or delamination under both static and cyclic loading which makes it a good candidate for strengthening thin-walled structural members, especially, when ductility is a concern. The 45° strengthening scheme (SP-6) performed better in both reducing the breathing phenomena (increasing the fatigue life expectancy) and increasing the ultimate shear capacity of the plate girders.

A geometrical and material non-linear FEA in commercial software was used to model the specimens used in this study and the proposed strengthening techniques. The unstrengthened model yielded reasonable results and was able to simulate the behaviour of the specimen throughout all loading stages, including the unloading stage. The strengthened model worked only up to the failure plateau, and the unloading path is being considered in on-going work.

7. References

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